Design and integration of heat pumps for nearly Zero Energy Buildings

Supported by:
Federal Ministry for Economic Affairs and Energy
on the basis of a decision by the German Bundestag

nZEB neighbourhoods

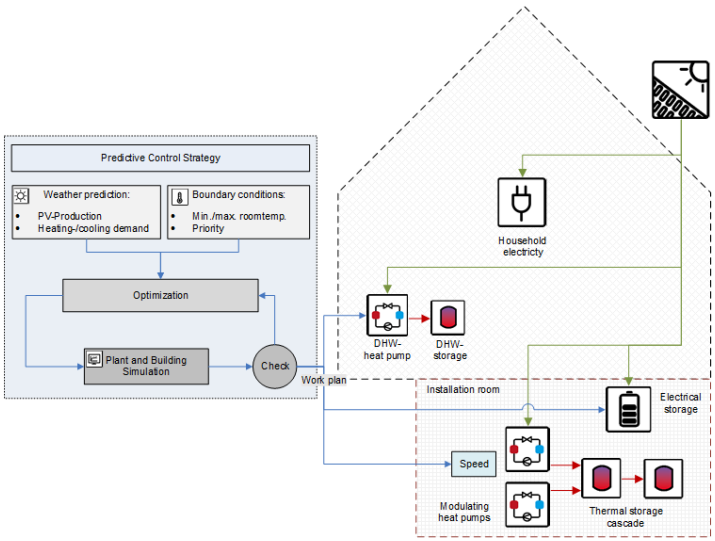
Herzogenaurach, Germany

Summary

The terraced houses, achieving “KfW Effizienzhaus 40 Plus”, has been monitored for two years from April 2018 - March 2020. The all-electric building is equipped with two central 17 kW ground-source heat pumps (B0/W35), eight decentral heat pumps for providing DHW and a 88 kW_p solar PV-system. Beside the buffer storage cascade of 2800 litres and eight DHW-storage tanks of 200 litre each, a 40 kWh battery serves as additional energy storage in order to increase the PV self-consumption. Moreover, decentral mechanical ventilation devices with 86 % heat recovery are installed. The ground-source is used for free-cooling in summer operation.

The plus energy balance has been reached in the two monitoring years. The ground-coupled heat pump system achieved an SPF of 5.6 and the DHW heat pumps achieved an SPF of 4.0, while the SPF of the whole energy system is 3.4. Optimized PV operation of the heat pumps led to an increase of the supply cover factor from about 32 % to around 37 %.

Concept



Building Data

Location:	Herzogenaurach, Germany
Building Use:	terraced houses
Energy ref. area (office/total)	1200 m^2
Walls	0.13 - 0.18 W/(m^2K)
Roof	0.13 W/(m^2K)
Ground floor	0.12 W/(m^2K)
Windows	0.7 – 0.8 W/(m^2K) triple glazing, g=0.5
Space heating demand	9.6 kWh/(m^2a)
DHW demand	20.9 kWh/(m^2a)

Background and current market state

In Germany, the “KfW Effizienzhaus 40 Plus” is defined by heating demand of 40 % and transmission heat loss of 55 % compared to the EnEV minimal requirement as well as additional technology equipment. This includes mainly a self-generated energy system, an electrical storage and mechanical ventilation with heat recovery. To demonstrate a more ambitious level, the terraced houses are also designed as plus energy building, which means a negative annual final energy demand including the whole energy balance incl. appliances.

Technical concept

The building was designed as an "all electric building", which means that the core source of energy is electricity. A roof PV system (88 kWp) delivers an annual surplus of energy. The idea of small neighbourhoods creating an energy community and share energy systems enables higher potential to increase the PV self-consumption. Furthermore, synergies between different electrical loads lead to an even electrical profile and reduces electrical load peaks. The terraced houses share a central heat pump system with geothermal source. The system consists of two modulating heat pumps (17 kW) in parallel operation in order operate to mainly in part load and use the high COP. Seven boreholes with 100 depth each deliver the heat source in winter and offer free cooling in summer. For the energy storage a buffer storage cascade (2800 l), eight DHW storage tanks (200 l) and a battery (40 kWh) are used. The building has a floor heating with design temperatures of 23 °C/27 °C, only the bathrooms have additional electrical radiators. The DHW is prepared serial by decentral DHW heat pumps (8x 2 kW), which use the buffer storage cascade as heat source.

The building is ventilated by mechanical ventilation devices with heat recovery of 86 %. Besides the floor heating, four terraced houses are equipped with ceiling heating. Both systems are used in defined periods separately in order to evaluate the thermal comfort.

Technical data of the unit

Heat pump

Alpha innoTec SWCV 162	
Heating capacity/COP	B0/W35: 17.2 kW/4.2
	B0/W55: 17.0 kW/3.2
Geothermal heat exchanger	7x 100 m
Alpha innoTec WWB 20	
Heating capacity/COP	B25/W50: 2.0 kW/4.4
	B20/W65: 1.5 kW/2.6

Solar PV system

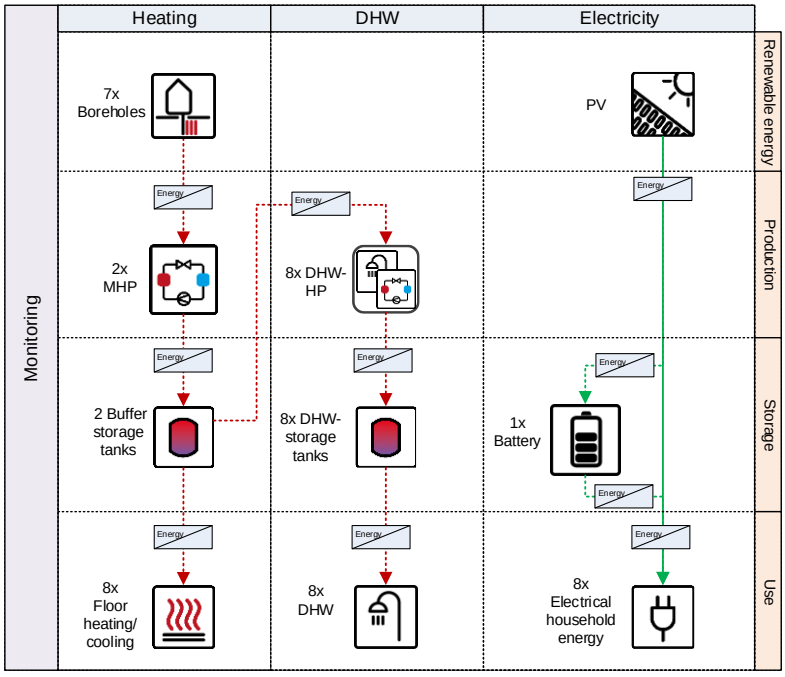
142 modules on the eastern roof	
150 modules on the western roof	
Total PV area:	426 m²
Peak power:	87.6 kW
Electrical efficiency	17.9 %

Storages

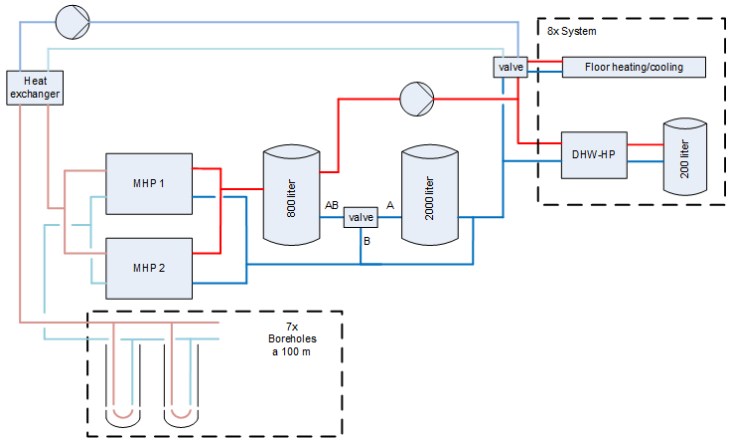
Heating buffer storage cascade	2800 l
DHW storage	8x 200 l
Battery	40 kWh

Ventilation systems

Max. Volume flow rate	1760 m³/h
Heat recovery	86 %



Measurement concepts and data loggers



Heating and DHW system concept

Field monitoring results

The objectives of the field monitoring is the evaluation of the plus energy balance. As further aspect the load match of energy communities use and PV yield is investigated in terms of self-consumption. In this context, also the use and availability of thermal and electrical storage units are of interest as local storage option. Moreover, the performance of the heat pumps is evaluated.

The monitoring period lasts from April 2018 to March 2020. The heat pump system reached a seasonal performance factor of SPF = 5.6 (4.9) in the first (second) year. The DHW heat pump system reached a SPF of 4.0 in both years. By the free-cooling operation, the SPF of the heat pump system is increased by 32 % to the warmer source (heat exchanger) and lower buffer storage temperature in summer. In the second monitoring period the SPF are quite constant over the year as the PV optimized control was commissioned and the heat pumps charge the buffer storage to higher temperatures. This results in a reduction of the SPF in summer.

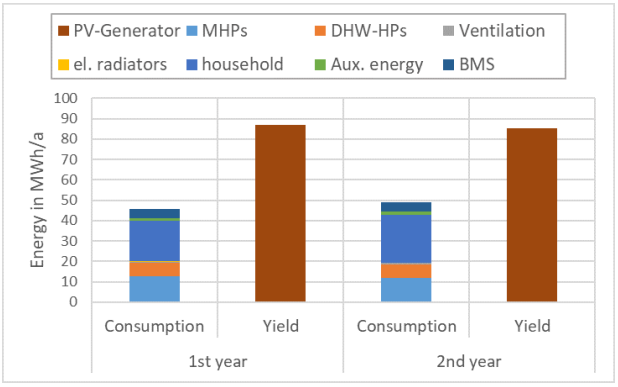
The total annual electricity consumption is about 38 kWh/(m²a) (45,729 kWh/a). The heat pump accounts for approx. 28 %, the DHW heat pumps about 14 %, the BMS about 10 % and household for approx. 43 % of the annual energy consumption.

The annual heating energy consumption (heating, DHW) is about 55 kWh/(m²a) (66,027 kWh/a). The room heating accounts for approx. 53 %, DHW production for approx. 35 % and free cooling for 12 % of the annual energy consumption.

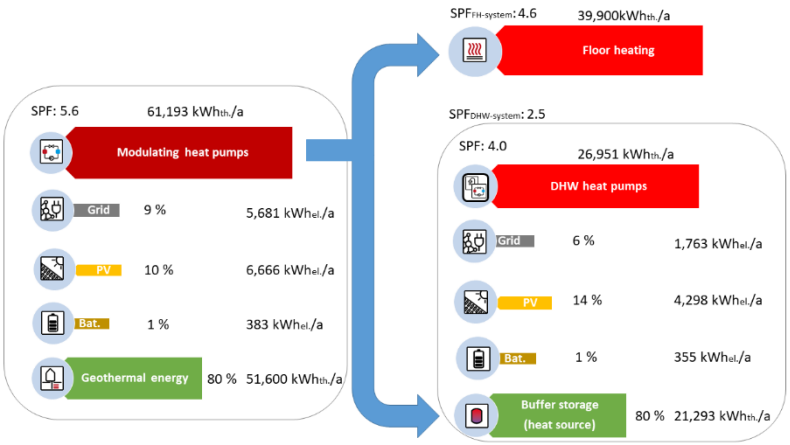
The yield of the solar PV is about 87,094 $kWh_{el.}$/a and delivers 43 % more than the annual electrical energy consumption. In the first year the final energy balance reached a value of -34.5 kWh/(m²a), i.e. a PV surplus of 34.5 kWh/(m²a) regarding the total consumption. The primary energy balance obtains a surplus of 62.0 kWh/(m²a).

Performance in Field monitoring

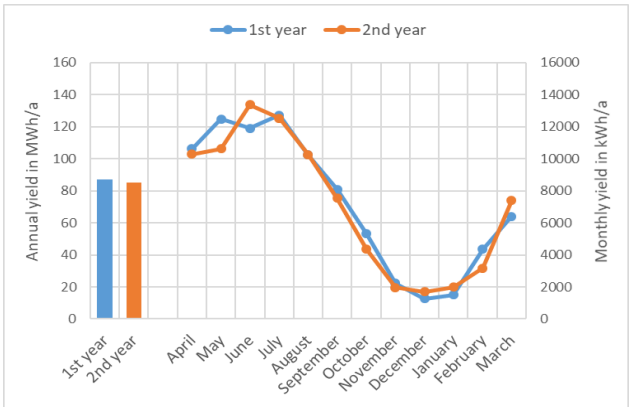
Seasonal performance factors	
SPF heat pump (boundary COP)	5.7 (5.1)
SPF DHW heat pump (boundary COP)	4.1 (4.1)
SPF system (all system components)	3.4 (3.3)
Solar PV yield	
Solar PV system	87,094 kWh (994 $kWh_{el.}/kW_p$)
nZEB balance (acc. "Efficiency House Plus")	
final energy	- 34.5 kWh/(m²a)
primary energy	- 62.0 kWh/(m²a)
Temporal characteristic	
(annual on 15 min step basis)	
Demand cover factor (self-consumption)	61 %
Supply cover factor (self-generation)	32 %



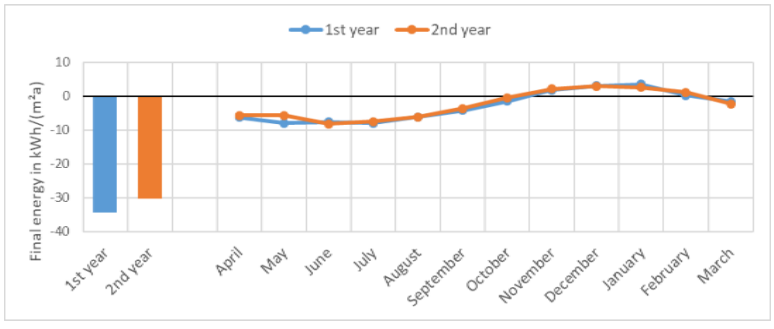
Annual Comparison of the consumption and production



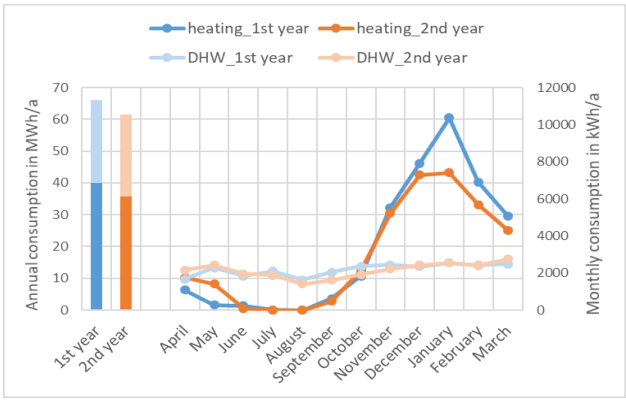
Heating and DHW flow diagram for first year from April 1, 2018 – March 31, 2019



Electric yield of the solar PV system in the two years



Monthly and annual nZEB balance for the two years



Annual and monthly heat consumption in the two years

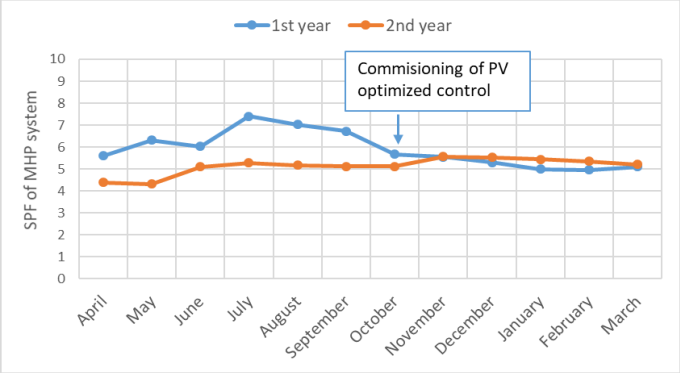
System performance and optimization

The overall system performance of the system is with 5.6/4.9 in a good range for ground-source heat pumps. By the heat exchanger for free cooling the heat pump tends to work at higher SPF. At the same time, higher storage temperatures due to PV optimized control relativize the good operation, and therefore, the SPF is quite constant over the year in the second monitoring period.

Based on the monitoring results of the first year optimization measures have been implemented and approved by the performance in the second year.

By the change of control strategy of the heat pumps, the PV self-consumption could be increased by 12.5 %. This results in an increase of the supply cover factor from 32 % up to 37 % and an increase of the load cover factor from 61 % up to 65 %. At the same time the PV yield decreased slightly by 2.2 %.

Another control strategy, which is tested for the energy system, is a model predictive control (MPC). On basis of weather and load prediction, the model predictive control creates an operation plan for each heat pump and the battery. In this case, the target and thus, the operation depends on the defined cost function.

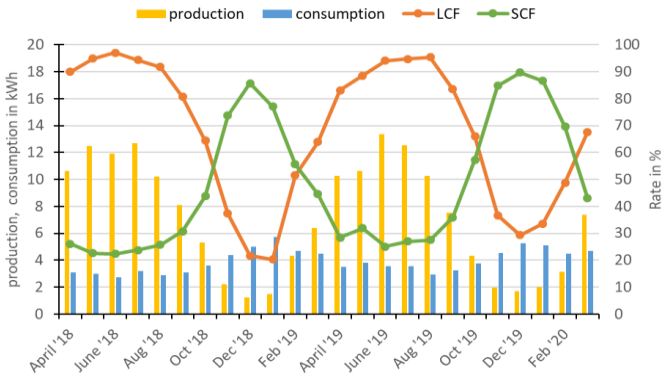


Monthly SPF of the MHP system in the two years

Economy, ecology, costs and self-consumption

At the time of monitoring, the electricity price is high and the feed-in tariff reduces, therefore, PV self-consumption is economically interesting. The cost gap of 0.21 €/kWh is within the range of generating cost of PV electricity and offers the potential of cost savings. Including the use of direct PV and battery, 61 % (65 %) of the total consumption is covered by self-generated electricity.

The average annual electricity surplus is about 38,000 kWh/a (about 120 % of the total electricity consumption). In the first (second) period under consideration, about 32 % (37 %) of solar power was used in the house itself, the vast majority being fed into the public grid.



Load/supply cover factor of two years for the total energy consumption

Imprint

Building owner
Private energy community

Design
Bär+Kühnhorn Architekten
Raab Baugesellschaft mbH&Co KG

Field monitoring
Technische Hochschule Nürnberg Georg Simon Ohm
Energie Campus Nürnberg - Energy efficient systems

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Literature references

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PV Optimized Control of Modulating Heat Pumps regarding PV Self-Consumption. Building Simulation 2019.

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Control Strategies for Geothermal Heat Pump Systems in Combination with Thermal and Electrical Storage Units. Building Simulation 2017

IEA HPT Annex 49

IEA HPT Annex 49 is a corporate research project on heat pump design and integration in nearly Zero Energy Buildings.
The project is accomplished in the Heat Pump Technologies (HPT) Technology Collaboration Programme (TCP) of the International Energy Agency (IEA).
Internet: http://www.heatpumpingtechnologies.org/annex49